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The Ogallala Agro-Climate Tool

Steve Mauget[a,b,*], Gary Leiker[a,b]

[a] U.S. Department of Agriculture-Agricultural Research Service, 3810 4th Street, Lubbock, TX 79415, United States
[b] USDA Plant Stress and Water Conservation Laboratory, Lubbock, TX, United States

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ABSTRACT

A Visual Basic™ agro-climate application capable of estimating crop evapotranspiration and irrigation demand over the Ogallala aquifer region is described here. The application's meteorological database consists of daily precipitation and temperature data from 141 U.S. Historical Climatology Network stations during 1976–2005. From that daily data the program calculates climate and crop evapotranspiration (ET_c) statistics over arbitrarily defined periods within summer or winter growing seasons at user-selected latitude–longitude coordinates. The statistics reported include: estimates of seasonal and sub-seasonal ET_c derived from the FAO-56 single crop coefficient algorithm, probabilities of exceedance of cumulative rainfall, irrigation demand and growing degree days, the probability that minimum and maximum daily temperatures will exceed user-defined temperature thresholds, and the probability of heat stress, cold stress and dry periods of varying duration.

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1. Introduction

Despite a generally semi-arid climate the Ogallala aquifer region (Fig. 1) is one of the United States most productive agricultural areas. The Ogallala states[1] include six of the top ten U.S. wheat producers and five of the top ten sorghum producers. Texas is the nation's leading grower of upland cotton, and together these states account for ∼40% of total U.S. cattle inventory and ∼70% of cattle in feedlots (National Agricultural Statistics Service, 2008). Much of this productivity is dependent on the aquifer's water, which lies under 45 million hectares of the Ogallala state's area. But over the latter half of the 20th and the first years of the 21st century pumping from irrigated agriculture has led to declines in saturated thickness that have not been compensated for by natural aquifer recharge (McGuire, 2007). This drawdown of an essentially fossil water resource has led to questions about the long-term viability of the area's agricultural economy (Brooks and Emel, 2000; Guerrero et al., 2008). Approaches to sustaining the region's economy might include changing agricultural practices to conserve the aquifer as a water resource for as long as possible, or preparing for the transition to predominantly dryland farming. Both responses require knowledge of the region's climatology and of the water requirements of the area's major crops. The Ogallala Agro-Climate Tool (hereafter, the "application"), a Visual Basic application that can be run on Windows 2000, XP, and Vista operating systems, was developed to provide that information.

This PC application's emphasis is on fundamental climatology. Unlike the comprehensive suite of tools offered by the AgClimate web application (Fraisse et al., 2006) or the Australian Rainman application (Clewett et al., 1992, 1994), the Ogallala tool does not forecast based on the phase of the El Niño–Southern Oscillation. Also, as the application is based on a historical meteorological database which is not continuously updated, it is not meant to be an operational decision support tool (e.g., Fernández and Trolinger, 2007). Instead, the focus is on the clear communication of accurate and high resolution climatological probabilities over the Ogallala region, and on agricultural water demand from a limited water resource. From a development standpoint, the Ogallala tool is a variant of a similar tool described in Mauget and De Pauw (2010), but is based on higher quality and more complete U.S. meteorological data. A screenshot of the Ogallala application's graphical user interface (GUI) can be found in Fig. 2 (For interpretation of the references to colour in this figure text, the reader is referred to the web version of this article.).

2. Primary meteorological data

The application's climate statistics are derived from daily minimum (T_{min}) and maximum (T_{max}) temperature and daily precipitation during 1976–2005. Daily data were provided by 141 meteorological stations selected from the U.S. Historical Climatology Network (USHCN; Menne et al., 2009), which are marked by red triangle icons on the large locator map (Fig. 2b). These data

* Corresponding author. Tel.: +1 806 723 5237; fax: +1 806 723 5271.
E-mail addresses: Steven.Mauget@ars.usda.gov (S. Mauget), Gary.Leiker@ars.usda.gov (G. Leiker).

[1] Texas, New Mexico, Oklahoma, Kansas, Colorado, Nebraska, South Dakota, and Wyoming.

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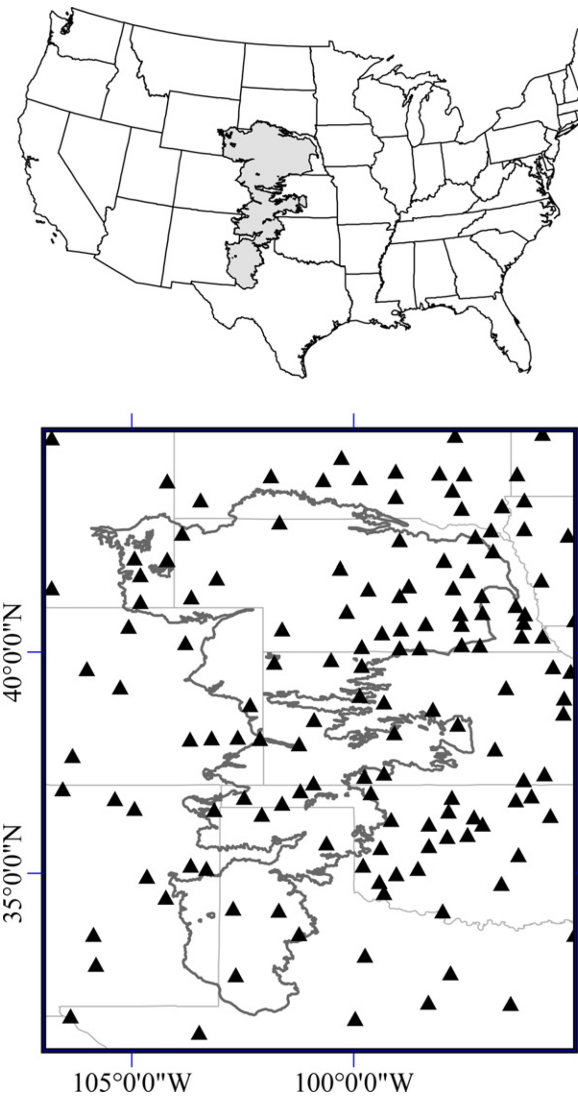

Fig. 1. The Ogallala aquifer region, with locations of the 141 meteorological stations used to provide data for the Ogallala Agro-Climate Tool.

are derived from a subset of the United States' cooperative station network that has undergone rigorous quality control (Menne and Williams, 2005, 2009). During 1976–2005 none of the 141 station's daily minimum temperature, maximum temperature, precipitation or snow records have more than 4% missing data, and a majority of station (135) have less than 3% missing data. Daily precipitation totals were estimated from daily rain and snow totals using a 12:1 (7:1) snow water equivalent ratio north (south) of 38° N latitude. Days with missing data were filled in with synthetically generated daily temperature or precipitation values (Hanson et al., 1994). In the application the records for each station's daily temperature and precipitation data during 1976–2005 are stored in a netCDF database (Rew and Davis, 1990) (For interpretation of the references to colour in this figure text, the reader is referred to the web version of this article.).

3. Calculation of climate statistics

In the application a location's climate statistics are typically estimated from data combined from more than one nearby station. Those stations can be selected automatically by left clicking the mouse on a location on the large locator map (Fig. 2b), or manually when the user right clicks on the map's station icons. A flow chart tracing the automatic selection of stations providing primary daily meteorological variables, i.e., $T_{\min}$, $T_{\max}$ and precipitation, can be found in Fig. 3a, and the corresponding flow chart for manual selection can be found in Fig. 3b.

The resolution of a selected location's climate statistics increases as the number of selected stations – marked by gold squares on the large map – increases. If, for example, a single station is selected either manually or automatically by the application's expanding radius search algorithm, the displayed seasonal precipitation statistics would be based on that station's 30 seasonal precipitation totals during 1976–2005. However, as probabilities based on 30 measurements provide only approximate statistical resolution, the user also has the option of calculating statistics from the data of more than one nearby station. Thus if more than one station is selected, seasonal precipitation probabilities on the Precipitation Tab are based on the precipitation totals from all the selected stations during 1976–2005. If two nearby stations were selected, the probability of exceedance values for seasonal precipitation (Fig. 2s) would be based on 60 station-seasons of data. If three were selected, exceedance probabilities would be based on 90 station-seasons of data, etc. This process also applies to the exceedance calculations for crop evapotranspiration (Fig. 2r), growing degree days (Fig. 2v), and the temperature and precipitation probabilities displayed on the calendar year display (Fig. 2g). Because the number of stations selected is limited to no more than 5, the distributions used to calculate seasonal climate probabilities can contain as many as 150 values. The selection of 4 or 5 stations might be considered ideal, as statistics based on 120 or more station-seasons of meteorological data allow for resolving climate probabilities to within 1%.

When the user selects an arbitrary location by left clicking on the Fig. 2b locator map, the nearest neighbor algorithm's search set of nearby stations are defined through an Access™ database (Fig. 3a). That database table divides the 12° longitude by 14° latitude Fig. 1 map region into 168 1° by 1° grid areas. The neighboring stations for a 1° by 1° grid area are the stations that lie within a 3° by 3° grid surrounding that central 1° grid. Once the application determines which 1° grid contains the selected location, the identifying netCDF station indices for the grid's neighboring stations are then retrieved from the Access database. The distances between the selected location and those stations are then calculated, and the stations are then sorted according to their distance from the selected location. If the nearest station is within 10 km, then that station's data is assigned to the location. Otherwise, between two and five of the nearest neighboring stations are selected using an expanding radius search algorithm. However, if there are no stations within 60 km this process can select stations in the surrounding 3° by 3° grid that are as far as 269 km away in the worst case.

To correct for the temperature effects of elevation between a selected location and nearby stations, the daily temperature values of neighboring stations are adjusted to the elevation of the selected location. This adjustment assumes a mean wet adiabatic atmospheric lapse rate of −6.5 °C/km. Station elevations are determined via the USHCN station inventory data, while a selected location's elevation is defined by the GTOPO30 digital elevation model (US Geological Survey, 2006).

The user also has the option of manually selecting up to five nearby stations by right clicking sequentially on each station's red triangle icon on the large locator map, then hitting the Control or Return key to calculate and display statistics. This station selection process can be made easier by first right clicking and dragging the mouse on the large locator map to zoom into a region of interest. The data retrieval and adjustment algorithm for manual selection (Fig. 3b) is similar to that for automatic selection (Fig. 3a), but the daily temperature values of each station are adjusted to the elevation of the average latitude–longitude coordinates of all the

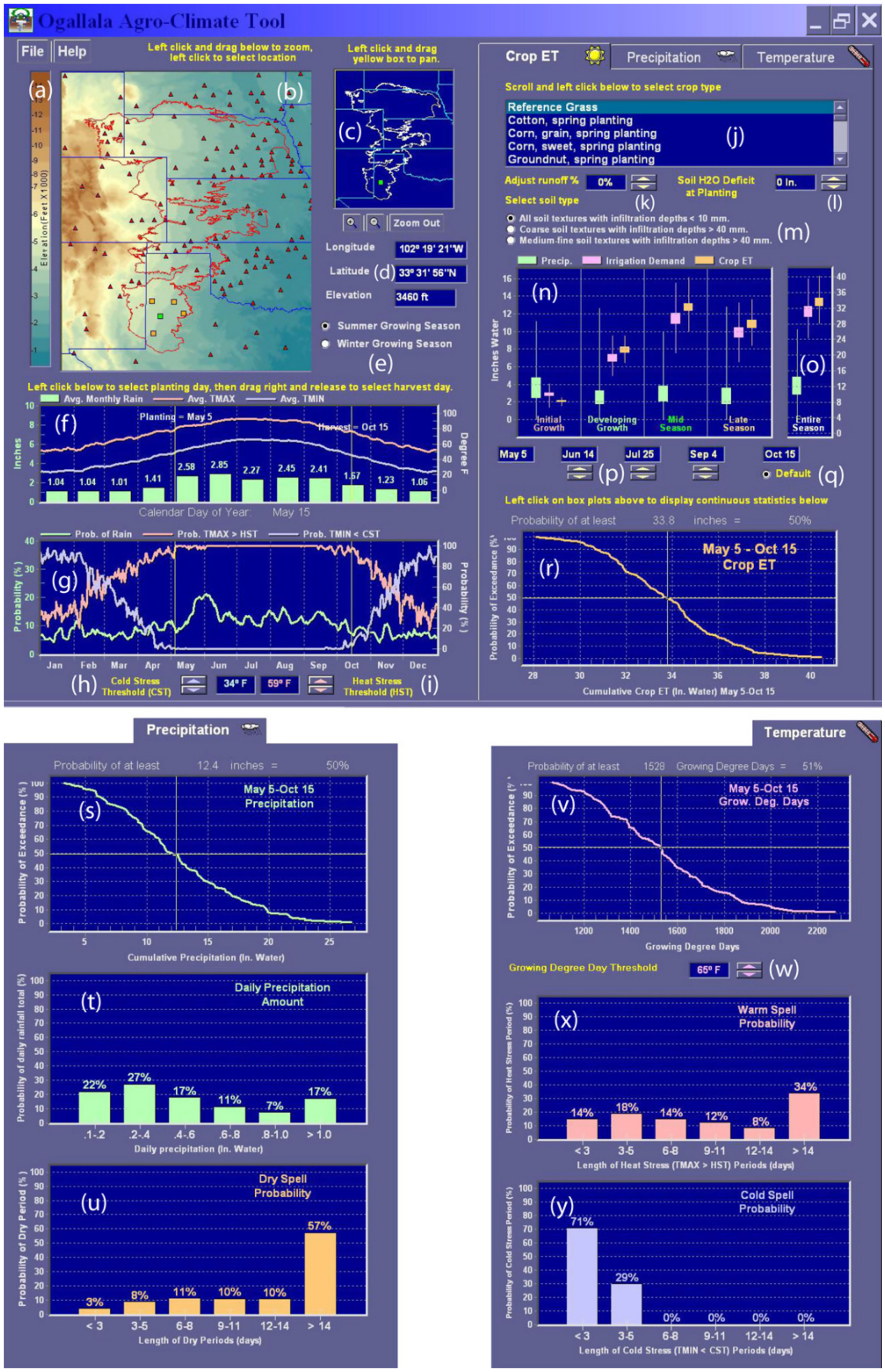

Fig. 2. The Ogallala Agro-Climate Tool graphical user interface. (a) Elevation legend for digital elevation model. (b) Location selection map. (c) Pan view map. (d) Longitude, latitude, elevation of selected location. (e) Growing season display selector. (f) Calendar year display: annual cycle of daily minimum (T_{min}) and maximum temperature (T_{max}) for selected location. (g) Calendar year display: probability of T_{min} and T_{max} exceeding user-defined heat stress and cold stress thresholds, and probability of rainfall. (h) Cold stress threshold (CST) spinner control and display. (i) Heat stress threshold (HST) spinner control and display. (j) Crop selection scroll list. (k) Percent runoff spinner control and display. (l) Soil moisture deficit at planting spinner control and display. (m) Soil type selector. (n) Crop ET, precipitation, and irrigation demand distributions for four crop growth periods. (o) Crop ET, precipitation, and irrigation demand distributions for entire growing season. (p) Crop growth period date displays and spinner selectors. (q) Reset selector to default FAO-56 growing season. (r) Probability of exceedance curve for Crop ET, precipitation, or irrigation distribution selected in (n) or (o). (s) Probability of exceedance curve for cumulative precipitation for period selected on calendar year display (f, g). (t) Probability that daily rainfall amounts will fall in one of five categories (<0.2 in, 0.2–0.4 in, 0.4–0.6 in, 0.6–0.8 in, 0.8–1.0, >1.0 in). (u) Probability of dry periods of varying lengths (<3 days, 3–5 days, 6–8 days, 9–11 days, 12–14 days, >14 days). (v) Probability of exceedance curve for growing degree days (GDD) for period selected on calendar year display (f, g). (w) GDD temperature threshold spinner selector and display. (x) Probability of heat stress periods of varying duration (<3 days, 3–5 days, 6–8 days, 9–11 days, 12–14 days, >14 days), for heat stress threshold defined by HST spinner selector (i). (y) Probability of cold stress periods of varying duration (<3 days, 3–5 days, 6–8 days, 9–11 days, 12–14 days, >14 days), for cold stress threshold defined by CST spinner selector (h).

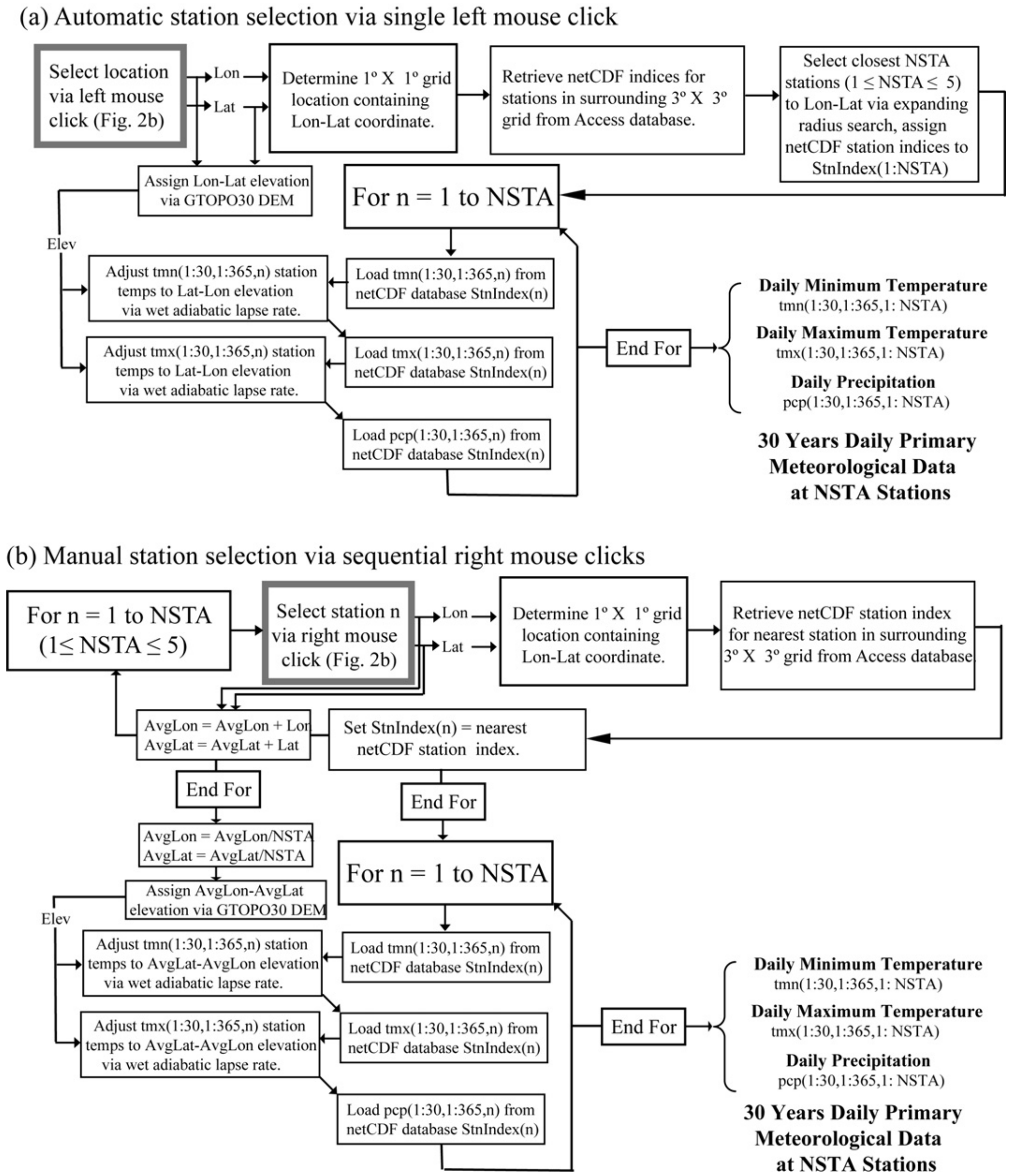

Fig. 3. Flow chart of the automatic selection of daily meteorological station data at a user-selected location using an expanding radius search method. (b) As in (a) for manual selection of meteorological stations. Gray outlined elements indicate a user control marked in Fig. 2.

selected stations. That location on the locator map is marked by a green square.

Once a user has selected a location by left clicking the mouse, or hit the Return or Control key after right clicking, the annual cycles of average daily $T_{\min}$ and $T_{\max}$ for each of the selected nearby stations are retrieved from the netCDF database. Those annual cycles of daily temperature – which have been smoothed using a moving 7-day boxcar average – are then elevation corrected to the selected location and averaged together. The average annual cycles are then displayed in the top graph of the calendar year display (Fig. 2f), together with average monthly rainfall. A location's average monthly rainfall is calculated as the average of the monthly averages of the selected stations. The calendar year display's bottom graph (Fig. 2g) shows the probability that daily $T_{\min}$ ($T_{\max}$) values will fall below (rise above) user-defined temperature thresholds (Fig. 2h,i), and the probability of daily precipitation. These probabilities are also calculated using running 7-day periods. Thus if one nearby station were selected, the precipitation probability for May 4 would be the total number of May 1–May 7 wet days at that station during 1976–2005, divided by the total number of days in that 7-day time window (210). If two stations were selected the May 4 precipitation probability would be the total number of May 1–May 7 wet days at both stations, divided by 420 days. In the application wet days are defined as having more than 2.54 mm (0.1 in) of total precipitation. Similarly, the probability that $T_{\min}$ will be below a cold stress threshold temperature (CST) is calculated as the total number of May 1–May 7 days at both stations when $T_{\min}$ < CST during 1976–2005, divided by 420 days. Periods with arbitrary beginning and end dates over which seasonal climate statistics are calculated can be defined by left clicking and dragging the mouse on either the top or bottom graph of the calendar year display. To define a winter seasonal period that begins before December 31 and ends after January 1, the same click and drag process can be used after clicking the 'Winter Growing Season' radio button (Fig. 2e). Although the application displays results in English units by default, SI units can be displayed by left clicking the 'File' button on the upper left of the GUI, then selecting 'Units' and 'SI'. Additional instructions for the application's use and descriptions of additional features can be found by left clicking the nearby 'Help' button.

Once a seasonal period is defined via the calendar year display the probability of exceedance of the period's total precipitation is displayed (Fig. 2s) on the Precipitation Tab. In addition a light green bar chart showing the probability of daily rainfall amounts (Fig. 2t) and a gold bar chart showing the probability of dry spells of various duration (Fig. 2u) during that period are also displayed. As described above, these probabilities are also calculated by aggregating statistics across the selected stations. The probability of daily rainfall amounts is calculated as the total number of wet days at the selected stations with rainfall totals in one of 6 classes (0.254–0.50, 0.50–1.0, 1.0–1.5, 1.5–2.0, 2.0–2.54, and >2.54 cm), divided by the total number of wet days within the seasonal period at all of the stations during 1976–2005. Similarly, dry spell probabilities are calculated as the number of dry days that occurred in spells of <3, 3–5, 6–8, 9–11, 12–14, or >14 days, divided by the total number of dry days within the seasonal period at all the selected stations during 1976–2005.

The Temperature Tab displays an exceedance curve for degree day accumulation (Fig. 2v), a light red bar chart showing the probability of heat (Fig. 2x) stress periods, and a light blue bar chart showing the probability of cold stress periods (Fig. 2y) of various duration during the growing season. Growing degree days (GDD) are calculated as the planting to harvest integral of the exceedance of daily mean temperature (i.e., $0.5 \times (T_{\min} + T_{\max})$) above a user-defined threshold (GDDT). That threshold can be adjusted over a 0.0–30.0 °C range (Fig. 2w). Thus,

$$\mathrm{GDD} = \sum_{i=\mathrm{PlantDOY}}^{\mathrm{HarvestDOY}} \mathrm{Max}(0.5 \times (T_{\max(i)} + T_{\min(i)}) - \mathrm{GDDT},\ 0.0) \tag{1}$$

The procedure for calculating the probabilities of temperature stress periods is similar to that for calculating dry spell probabilities. That is, given the definition of a hot day as a day when $T_{\max}$ is greater than a user-defined heat stress threshold (HST; Fig. 2i), heat spell probabilities are calculated as the total number of hot days occurring in unbroken sequences of <3, 3–5, 6–8, 9–11, 12–14, or >14 days, divided by the total number of hot days within the seasonal period at all the selected stations during 1976–2005. Cold spell probabilities are calculated similarly but with an inverse logic; i.e., cold days are defined as those when $T_{\min}$ is less than the CST cold stress threshold (Fig. 2h).

4. Crop evapotranspiration and irrigation demand

On the Crop ET Tab (Fig. 2j–r) the application displays crop evapotranspiration ($\mathrm{ET_c}$) for 81 crop types calculated via the FAO-56 single crop coefficient algorithm (Allen et al., 1998). These $\mathrm{ET_c}$ values reflect the cumulative evaporative demand from crops grown in large fields under optimum soil water and excellent management and environmental conditions, and that are otherwise capable of achieving full production under given climatic conditions. A flow chart describing the calculation of $\mathrm{ET_c}$ and its associated secondary meteorological variables can be found in Fig. 4a. The single coefficient algorithm calculates crop ET as the evapotranspiration of a reference alfalfa crop multiplied by crop-specific coefficients that vary over four growing season periods (Fig. 4b):

- an initial growth period, defined as occurring between planting and approximately 10% ground cover,
- a developing growth period, defined as occurring between 10% ground cover and effective full cover,
- a mid-season period that runs from effective full cover to the start of maturity, where maturity is indicated by the beginning of senescence of leaves, leaf drop, or the browning of fruit,
- and a late-season period, which lasts from the start of maturity to harvest or full senescence.

When a crop is selected on the crop selection scroll list (Fig. 2j) the application presents results for preset planting and harvest dates and crop growth periods that can be adjusted by the user. Planting and harvest dates for a selected crop can be redefined by adjusting the growing season length via clicking and dragging on the calendar year display as described in Section 3. The other beginning and end dates of the four crop growth periods can be adjusted via the spinner controls (Fig. 2p) below the growing season display on the Crop ET tab (Fig. 2n). During each growth period irrigation demand (ID) is calculated as the total amount of water that must be added to effective precipitation ($\mathrm{PCP_e}$) to maintain soil moisture at maximum holding capacity, i.e., field capacity, during the growing season. Following the FAO-56 daily soil water balance equation (Allen et al., 1998, Eq. (85)) irrigation demand on day i is given by,

$$\mathrm{ID}_i = \mathrm{ET}_{\mathrm{c}(i)} - \mathrm{PCP}_{\mathrm{e}(i)} - \mathrm{CR}_i + \mathrm{DP}_i \tag{2}$$

where $\mathrm{ET}_{\mathrm{c}(i)}$ is the FAO-56 crop ET on day i, effective precipitation ($\mathrm{PCP}_{\mathrm{e}(i)}$) is precipitation minus runoff (RO_i), i.e., the portion of daily precipitation (PCP_i) available to the crop,

$$\mathrm{PCP}_{\mathrm{e}(i)} = \mathrm{PCP}_i - \mathrm{RO}_i, \tag{3}$$

CR_i is the amount of soil water transported upward to the root zone via capillary rise and DP_i is root zone water loss by deep percolation. The application's soil water balance equation assumes that both CR_i and DP_i are negligible. Three general soil types (HERE).

Runoff is defined as a percentage of daily precipitation (% RO), which can be adjusted in 5% increments on the Crop ET tab (Fig. 2k).

$$\mathrm{RO}_i = \mathrm{PCP}_i \times \%\mathrm{RO} \times 0.01 \quad (0 < \%\mathrm{RO} < 100) \tag{4}$$

Based on these definitions and assumptions, and the runoff percentage defined by the user, the application calculates irrigation demand for each day from the corresponding daily $\mathrm{ET_c}$ and precipitation value. Daily irrigation demand is limited to positive values, i.e.,

$$\begin{aligned} \mathrm{ID}_i &= \mathrm{Max}(\mathrm{ET}_{\mathrm{c}(i)} - \mathrm{PCP}_i \times (100 - \%\mathrm{RO}) \times 0.01, 0.0) \\ &= \mathrm{Max}(\mathrm{ET}_{\mathrm{c}(i)} - \mathrm{PCP}_{\mathrm{e}(i)}, 0.0) \end{aligned} \tag{5}$$

The cumulative ID values for the four crop growth periods (Fig. 2n) and the entire growing season (Fig. 2o) used to form the purple box and whisker distributions on the Crop ET tab are the sum of the daily calculated values during those periods. During the initial crop growth period an additional term (I_{Planting}) accounts for the amount of irrigation required to increase soil moisture at planting to field capacity. If PlantDOY is the day of the year on which planting occurs and δ is the length of the initial crop growth period in days,

$$\mathrm{ID}_{\mathrm{initial}} = \sum_{i=\mathrm{PlantDOY}}^{\mathrm{PlantDOY}+\delta} \mathrm{ID}_i + I_{\mathrm{Planting}} \tag{6}$$

The amount of irrigation applied at planting can be defined by the user in 2.54 cm increments via a spinner control on the Crop ET tab (Fig. 2l). The gold and light green bar and whisker diagrams in Fig. 2n and o are the corresponding distributions of total $\mathrm{ET_c}$ and precipitation for those sub-seasonal and seasonal periods.

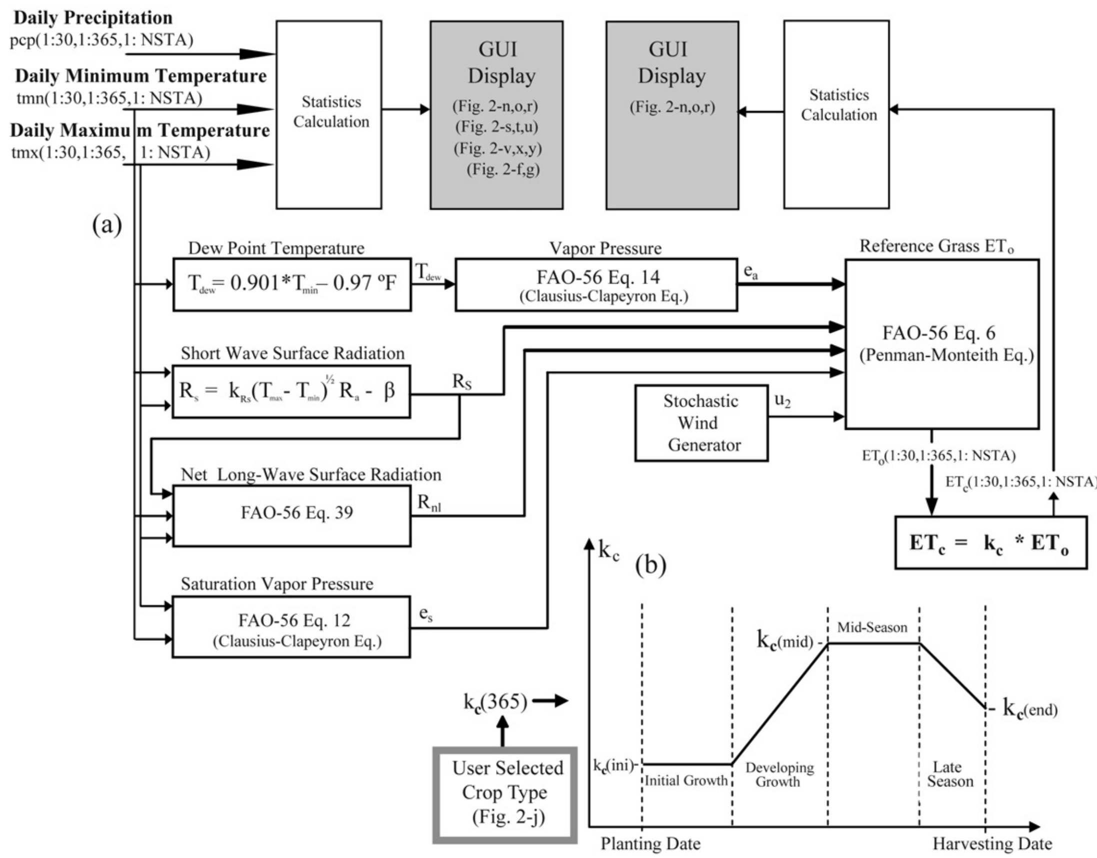

Fig. 4. (a) Flow chart of the generation of daily secondary weather and crop evapotranspiration variables. Gray outlined elements indicate a user control, and gray shaded elements indicate a display marked in Fig. 2. (b) Growing season coefficient profile for the FAO-56 single coefficient crop evapotranspiration method.

5. Generation of secondary weather variables

The secondary daily meteorological variables needed to calculate ET_c were derived here using parameterization schemes drawn from the FAO-56 (Allen et al., 1998). Parameters specific to the Ogallala region were calculated using data from the High Plains Regional Climate Center's Automated Weather Data Network (AWDN). The AWDN data set provides daily and hourly measurements of T_{min}, T_{max}, precipitation, surface shortwave radiation (R_S), relative humidity (RH), and 2 m wind speed (U_2) during 1998–2004. For reference to the generation of secondary variables, see the Fig. 4a flow chart.

5.1. Dew point temperature

Following FAO-56 Eq. (6–6), daily dew point temperatures (T_{dew}) for USHCN stations were estimated from the same day's minimum temperature using the following linear equation,

$$T_{dew(i)} = 0.901 \times T_{min(i)} - 0.97, \tag{7}$$

where $T_{dew(i)}$ and $T_{min(i)}$ are dew and minimum temperatures for day i in degrees Fahrenheit. Eq. (7)'s linear coefficient and regression constant were derived via regression of daily T_{min} and T_{dew} data from four AWDN stations during 1998–2004. Daily T_{dew} in the AWDN data was derived from T_{min}, T_{max}, and RH via the Clausius–Clapeyron equation ($e^0(T)$: FAO-56 Eq. (11), Eqs. (3)–(11)).

5.2. Vapor pressure and saturation vapor pressure

Given daily T_{min}, T_{max} in the USHCN data and derived T_{dew}, the daily vapor pressure and saturation vapor pressure are determined using $e^0(T)$.

$$\text{Saturation vapor pressure for day } i = e_{s(i)} = 0.5 \times (e^0(T_{max(i)}) + e^0(T_{min(i)})) \tag{8}$$

$$\text{Actual vapor pressure for day } i = e_{a(i)} = e^0(T_{dew(i)}) \tag{9}$$

5.3. Shortwave radiation at the surface

Following the Hargreaves radiation formula (FAO-56 Eq. (50)) integrated daily shortwave surface radiation (R_S) was calculated for each USHCN station from daily temperature and daily integrated shortwave radiation at the top of the atmosphere using Eq. (10):

$$R_{S(i)} = k_{Rs}\sqrt{T_{max(i)} - T_{min(i)}}R_{a(i)} - \beta \tag{10}$$

where, k_{Rs} and β are coefficients were determined by regression analysis of AWDN daily temperature and R_S data. The linear coefficient (k_{Rs}) was assigned a value of 0.165 °C$^{-0.5}$, and the regression constant (β) was assigned a value of $1.504\,\text{J} \times 10^6/(\text{met.}^2 \times \text{day})$. $T_{min(i)}$ is the minimum temperature for day i in degrees Celsius. $T_{max(i)}$ is the maximum temperature for day i degrees Celcius. $R_{a(i)}$ is the daily integrated shortwave radiation at the top of the atmosphere calculated for each day of the year (FAO-56 Eq. (21)) in units of $\text{J} \times 10^6/(\text{met.}^2 \times \text{day})$.

5.4. Net outgoing long-wave radiation (OLR) at the surface

Daily net upwelling surface OLR (R_{nl}) was estimated using FAO-56 Eq. (39):

$$R_{nl(i)} = \sigma \left[\frac{T^4_{\max(i)} + T^4_{\min(i)}}{2} \right] \left(0.34 - 0.14\sqrt{e_{a(i)}}\right) \times \left(1.35 \frac{R_{S(i)}}{\tau \times R_{a(i)}} - 0.35\right) \quad (11)$$

where, σ is the Stefan–Boltzmann constant, $T_{\min(i)}$ is the minimum temperature for day i in degrees Kelvin, $T_{\max(i)}$ is the maximum temperature for day i in degrees Kelvin, $R_{S(i)}$ is the estimated daily shortwave radiation at the surface (Eq. (10)), $\tau \times R_{a(i)}$ is the estimated clear sky daily shortwave radiation at the surface. Clear sky short wave transmissivity (τ) was assigned a value of 0.66 based on the mode of the distribution of daily R_S/R_a ratios in AWDN station data. $e_{a(i)}$ is the actual vapor pressure (Eq. (9)).

5.5. Wind speed

The application's daily average U_2 values are generated using a scheme adapted from the Hanson et al. (1994) temperature generation approach, but with wind speeds randomly defined by two parameter Weibull wind speed distributions (Hagen, 1991). Weibull shape and scale parameters were derived from distributions of daily AWDN wind data in the central and northern Ogallala region. In the southern portion of the Ogallala region U_2 records from the U.S. cooperative station data network (U.S. National Weather Service, 2000) were used.

5.6. Reference grass evapotranspiration

The FAO-56 method for deriving evapotranspiration rates for various crops is based on the estimation of reference evapotranspiration rates over a hypothetical short grass or alfalfa surface (FAO-56 Chapter 4). Daily reference short grass ET rates (ET_o) are calculated in the application using the FAO-56 Penman–Monteith equation (FAO-56 Eq. (6)).

$$ET_{o(i)} = \frac{0.408\Delta((1-\alpha)R_{S(i)} - R_{nl(i)} - G) + \gamma \frac{900}{T_i} U_{2(i)}(e_{s(i)} - e_{a(i)})}{\Delta + \gamma(1 + 0.34U_{2(i)})} \quad (12)$$

where, Δ is the slope of the saturation vapor pressure at the mean daily temperature (FAO-56 Eq. (3–3)), α is the surface albedo of a shortgrass surface (=0.23), $R_{S(i)}$ is the daily shortwave solar radiation at the Earth's surface (Eq. (10)), $R_{nl(i)}$ is the daily net upwelling outgoing long-wave radiation (OLR) at the surface (Eq. (11)), G is the soil heat flux density (FAO-56 Eq. (5–2), with an assumed Leaf Area Index of 2.8), γ is the Psychometric constant (FAO-56 Eq. (8)), T_i is the daily mean (i.e., $0.5(T_{\max(i)} + T_{\min(i)})$) temperature in Kelvin, $U_{2(i)}$ is the generated value of daily mean wind speed at 2 m (Section 5.5), $e_{s(i)}$ is the saturation vapor pressure (Eq. (8)), and, $e_{s(i)}$ is the actual vapor pressure (Eq. (9)).

5.7. Crop evapotranspiration calculation

The application derives crop evapotranspiration rates over default FAO-56 growing seasons for 81 crops listed in the selection box at the top of the 'Crop ET' Tab (Fig. 2j). Daily crop ET rates are derived from a location's derived reference grass ET rates (Eq. (12)) using the FAO-56 single crop coefficient method (FAO-56 Eq. (58)).

$$ET_{c(i)} = k_{c(i)} ET_{o(i)} \quad (13)$$

Over the growing season crop ET is calculated using $k_{c(i)}$ values drawn from a growing season coefficient profile (Fig. 4b). Those daily coefficient values are in turn derived from three k_c values defined during an initial crop growth period, a mid-season period, and an end of season value. Initial k_c values are calculated based on estimates of total and readily available water in the surface soil layer, the mean interval between wetting events, and the average soil water evaporation rate during the initial growth period (FAO-56 Annex 7, Eq. (7–3)). Those initial coefficient values are also dependent on the soil type selected on the GUI by the user (Fig. 2m), who has the option of specifying any soil texture with infiltration depths <10 mm, or either fine or coarse soil textures with infiltration depths ≥40 mm. Tabulated k_c values for the mid- and end-season periods (FAO-56 Table 12) are adjusted based on mean U_2 and RH conditions calculated during those periods (FAO-56 Eqs. (62 and 65)).

Doorenbos and Kassam (1979) cite an unbiased error of 10–20% for Eq. (13)'s ET_c estimates if the meteorological data are reliable and measured at a location representative of a producer's field conditions. However, while the application's daily temperature data can be considered reliable, USHCN stations may not always be sited in locations representative of Ogallala growing conditions. This may be particularly true in the region's irrigated semi-arid western areas. In these areas station temperature data may have a warm bias relative to cooler temperatures over large irrigated fields, which can lead to a corresponding positive bias in ET_o values calculated from the station's temperature data. Because of this possible ET_o bias over irrigated semi-arid and arid areas, Doorenbos and Pruitt (1977) estimate that Eq. (13) may over predict ET_c by 5–15% in fields of 5–20 ha, and 20–25% in extended areas where cropping density approaches 100%. Another source of ET_c bias may occur in areas where wind velocities are reduced by real or artificial windbreaks. In such areas – which are relatively rare in the Great Plains – ET_c estimates based on Section 5.5's assumed U_2 distributions might under predict crop ET in wind sheltered plots. This negative bias can vary by 5–30% depending upon the plot's distance from the windbreak and the windbreak's height.

6. Summary

The Ogallala Agro-Climate Tool is a Visual Basic™ agro-climate application that provides estimates of climate statistics, crop evapotranspiration and irrigation demand over the United States' Ogallala aquifer region (Fig. 1). The application (Fig. 2) calculates and displays agriculturally relevant seasonal climate statistics for a location via the aggregation of nearby meteorological station data statistics. Stations can be selected manually (Fig. 3a) or by an expanding radius search algorithm that limits the aggregation to data from nearby stations (Fig. 3b). As this search algorithm is limited to a 3° longitude by 3° latitude grid centered on the location selected by the user, the application has similar or finer spatial resolution. When statistics are calculated from four or more stations the application presents seasonal climate probability distributions with a statistical resolution of better than 1%. These distributions can be calculated for arbitrary periods, as seasonal periods can be defined with user-selected beginning and end days. The daily meteorological station data on which the software is based is the most quality-controlled U.S. data available, thus the application provides high resolution and high-quality climate information.

The application also displays distributions of crop evapotranspiration for a range of crops derived via the FAO-56 single coefficient crop ET algorithm. These estimates apply to standard conditions as defined by the FAO-56; i.e., crops grown under disease free and optimal soil water conditions, and capable of full production under specified climate conditions. Based on these crop ET estimates, and precipitation data from the meteorological database, the application displays probability distributions of the crop's irrigation demand based on a simplified soil water balance equation (Eq. (5)).

7. Downloading, operating requirements and instructions

The Ogallala Agro-Climate Tool can be downloaded at: http://www.ogallala.ars.usda.gov/OgAgCliTool_Install.HTML

The application should be installed on a Windows PC with a Pentium III or better microprocessor and requires 61 Mbytes of available hard disk space. Monitor screen resolution should be at least 1024 × 768 pixels. The bright yellow text on the graphical user interface provides basic operating instructions. To access help for a specific control or graph, left mouse click on that object and hit 'F1'. More detailed instructions for the application's use can be found by left single clicking on 'Help' on the application's upper left corner.

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